Use of Crab Cavities for Short X-ray Pulse Production in Rings

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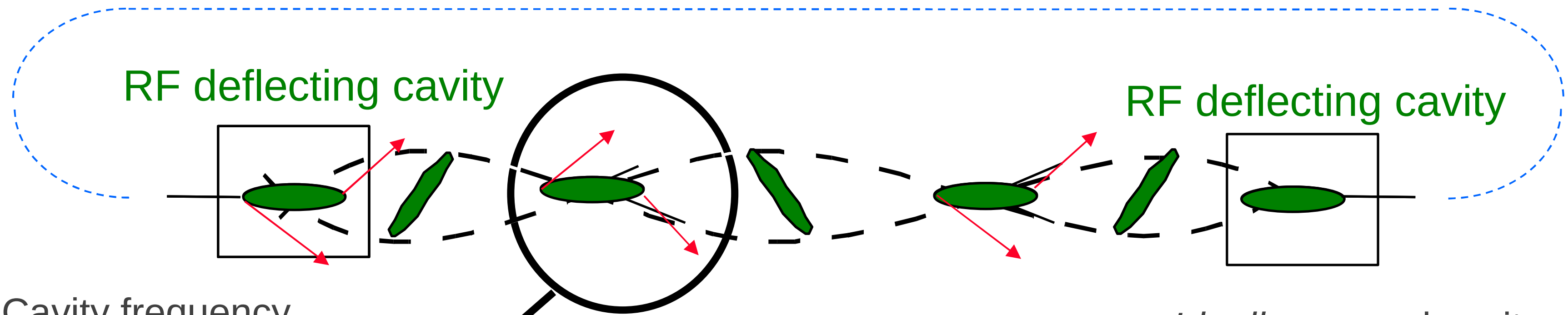
Outline

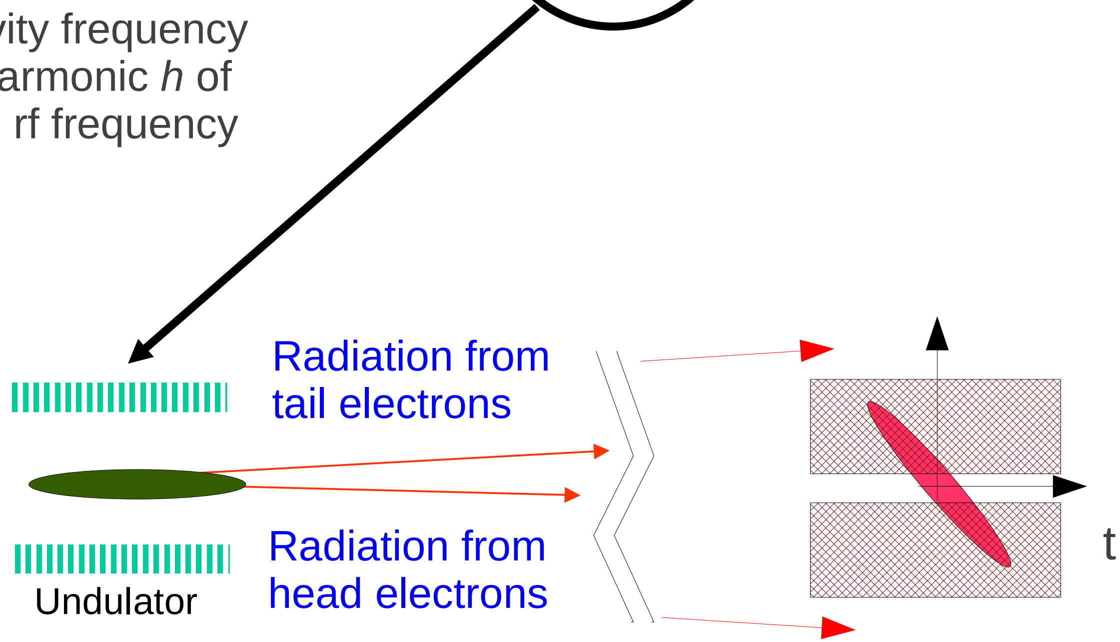
- Review of Zholents' concept
- Basic analysis of x-ray slicing
- Lattice options
- Simulation code and methods
- Emittance degradation mechanisms
- Error sensitivities
- Photon beam modeling and predictions

Zholents' Transverse Rf Chirp Concept[1]



Cavity frequency is harmonic *h* of ring rf frequency

Ideally, second cavity exactly cancels effect of first if phase advance is n*180 degrees



Pulse can be sliced or compressed with asymmetric cut crystal

(Adapted from A. Zholents' August 30, 2004 presentation at APS Strategic Planning Meeting.)

[1]A. Zholents *et al.*, NIM A 425, 385 (1999).

Estimating X-ray Pulse Duration

- X-ray pulse duration can be estimated assuming gaussian distributions[1]

Electron beam energy

$$\sigma_t \approx \frac{E}{\frac{\partial V}{\partial t}} \sqrt{\frac{\beta_{id}}{\beta_{rf}}} \sqrt{\frac{\epsilon_y}{\beta_y} + \sigma^2_{y',rad}}$$

For 4 MV, 2.8GHz (h=8) deflecting system, get ~0.6 ps

Rate of change of deflecting voltage

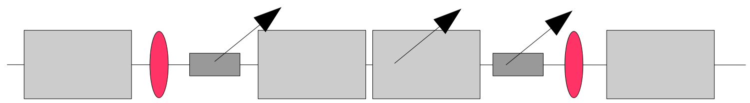
Unchirped e-beam divergence (typ. 2-3 μrad)

Divergence due to undulator (typ. ~5 μrad)

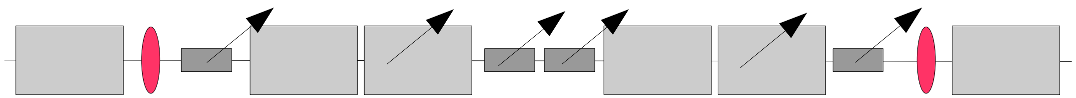
- Vertical emittance matters because it affects the electron beam divergence

[1]M. Borland, PRSTAB 8, 074001 (2005).

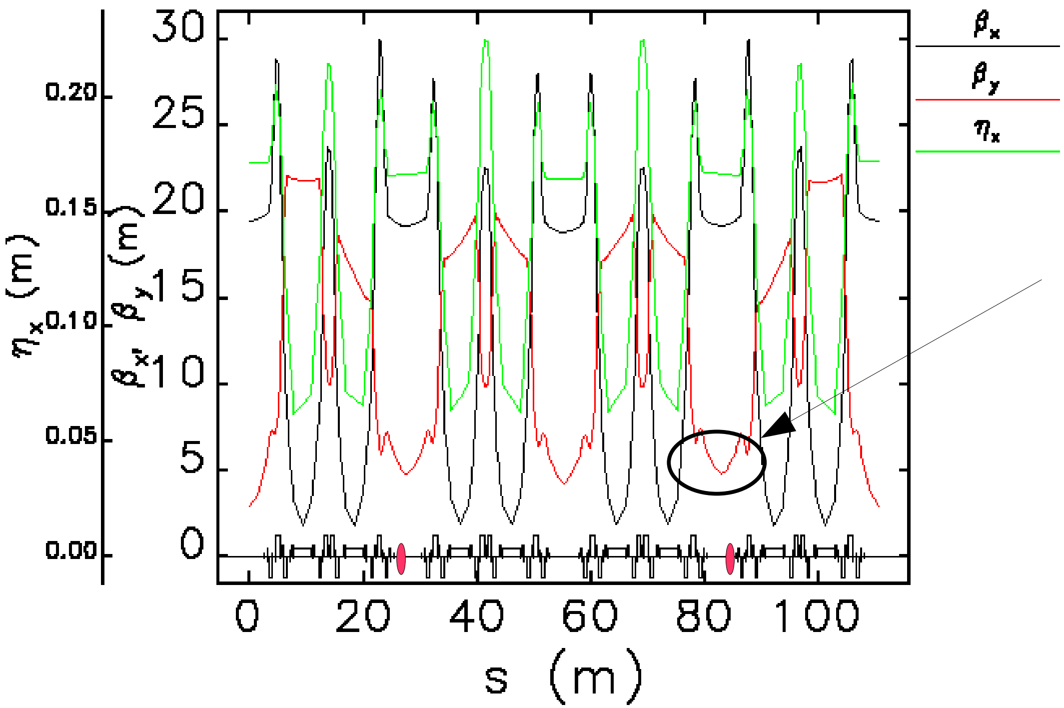
Lattice Options



1 sector spacing
2 ID + 1 BM



2 sector spacing
4 ID + 2 BM



Beta function increase required to get the right phase advance

Helps compression by making divergence smaller

After V. Sajaev, ASD/APG/2004-11

Simulation Code and Methods

- Used **elegant**[1] for all simulations
  - Parallel version used for most computations[2]
- Modeled lattice with
  - First-order bending magnets (ρ=38m)
  - Canonically-integrated quadrupoles and sextupoles
- Modeled deflecting cavities with RFDF (RF DeFlector) element
  - Idealized top-hat longitudinal and radial field profile
- Synchrotron radiation modeled with a lumped element (SREFFECTS)
  - Gives correct damping rates and equilibrium properties

[1]M. Borland, APS LS-287, Sept. 2000.
[2]Y. Wang et al., Proc. PAC2007, THPAN095, jacow.org.

Emittance Degradation[1]

- Second cavity can't *exactly* cancel effect of first
  - Vertical emittance will grow
- Effects present in a perfect machine
  - Momentum compaction and beam energy spread
    - Rms phase spread in second cavity relative to first
  - Sextupoles between cavities
    - Amplitude-dependent phase advance variation in transport between the cavities
    - Coupling from y to x
  - Chromaticity and beam energy spread
    - Rms phase advance spread in transport between cavities
- Additional effects in an imperfect machine
  - Lattice errors
  - Rolled elements between cavities
  - Roll of cavities about beam axis
  - Rf phase and voltage errors

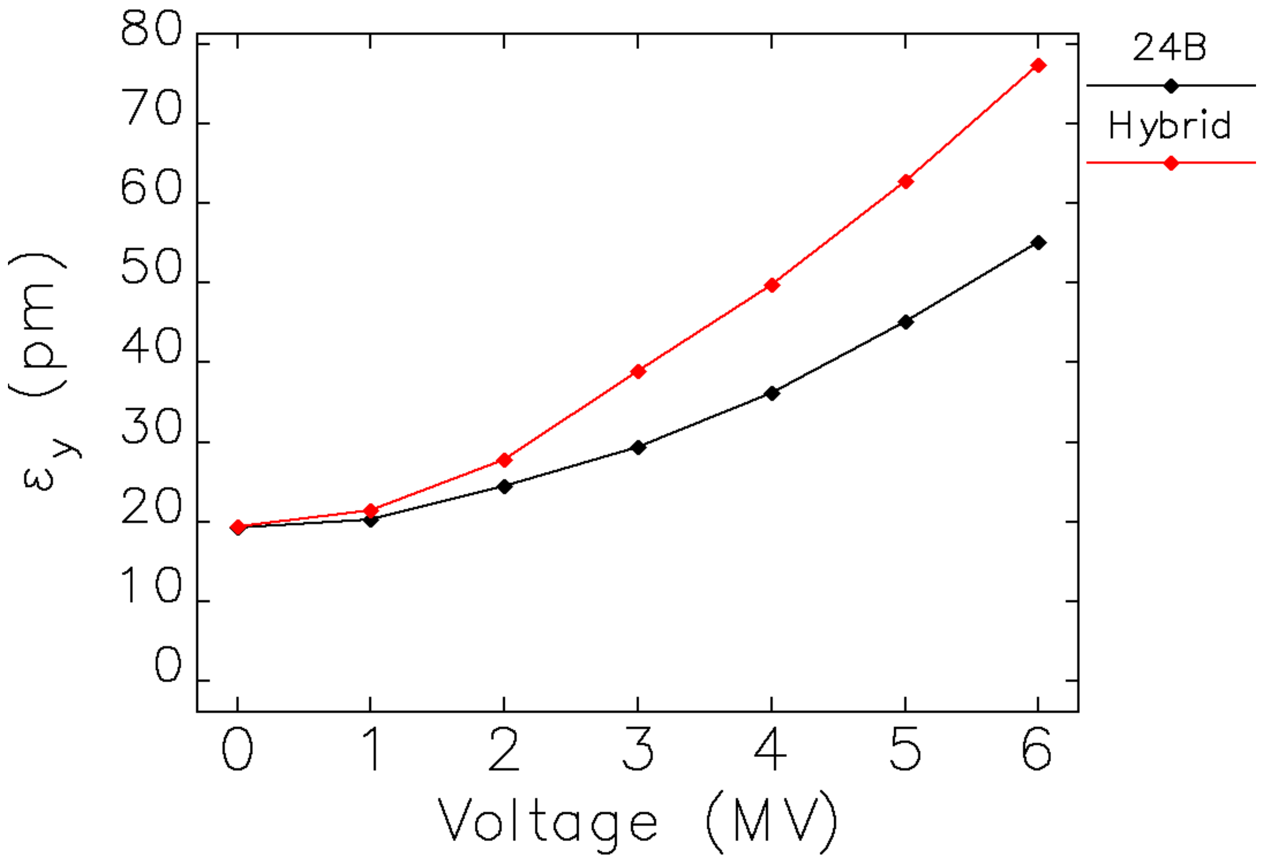
[1]M. Borland, PRSTAB 8, 074001 (2005).

Optimizing Sextupoles

- Sextupoles are the dominant emittance growth source
- APS has individual supplies for each sextupole
  - We can tune the sextupoles to minimize emittance growth[1]
  - Use optimizer in **Pelegant** to vary interior sextupoles and minimize the single-pass growth
- Important factors in making this work[2,3]
  - Use lattice with lower vertical beta functions
  - Small/zero chromaticity between cavities
  - Don't let sextupoles change too much
- If these are not respected, dynamic aperture is hard to recover

[1] M. Borland, PRSTAB 8, 074001 (2005).
[2] V. Sajaev, ASD/APG/2005-06
[3] M. Borland and V. Sajaev, Proc. PAC2005, 3886-3888.

Emittance Growth for Optimized Configurations

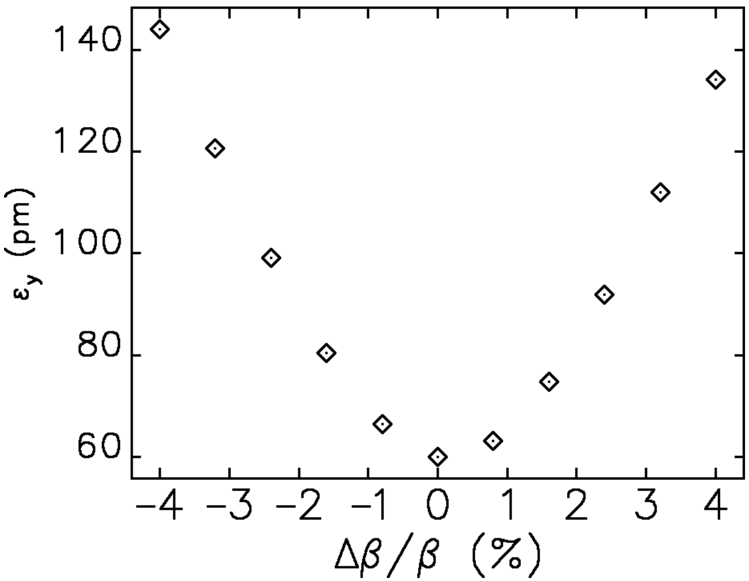


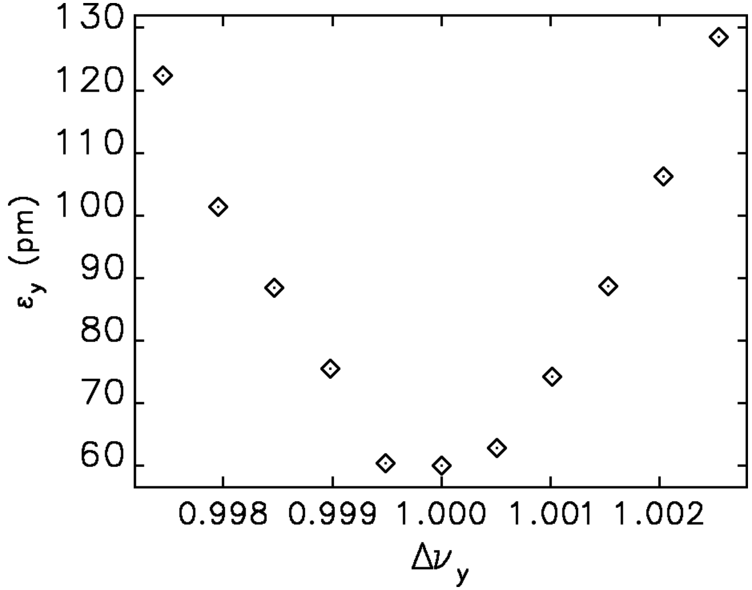
- Starting vertical emittance is 20 pm (0.8% coupling)[1]
  - Normal operation is 30~40 pm
- Working points based on present operations[1]
- Hybrid-mode results are for intense bunch only

[1]L. Emery, private communication.

Lattice Errors

- Lattice errors can result in
  - Phase advance errors
  - Beta function errors
- Sources include
  - Beamline steering
  - Power supply drift
  - Misalignments
- Lattice correction gives
  - 1% beta function errors[1]
  - <0.001 tune error[2]

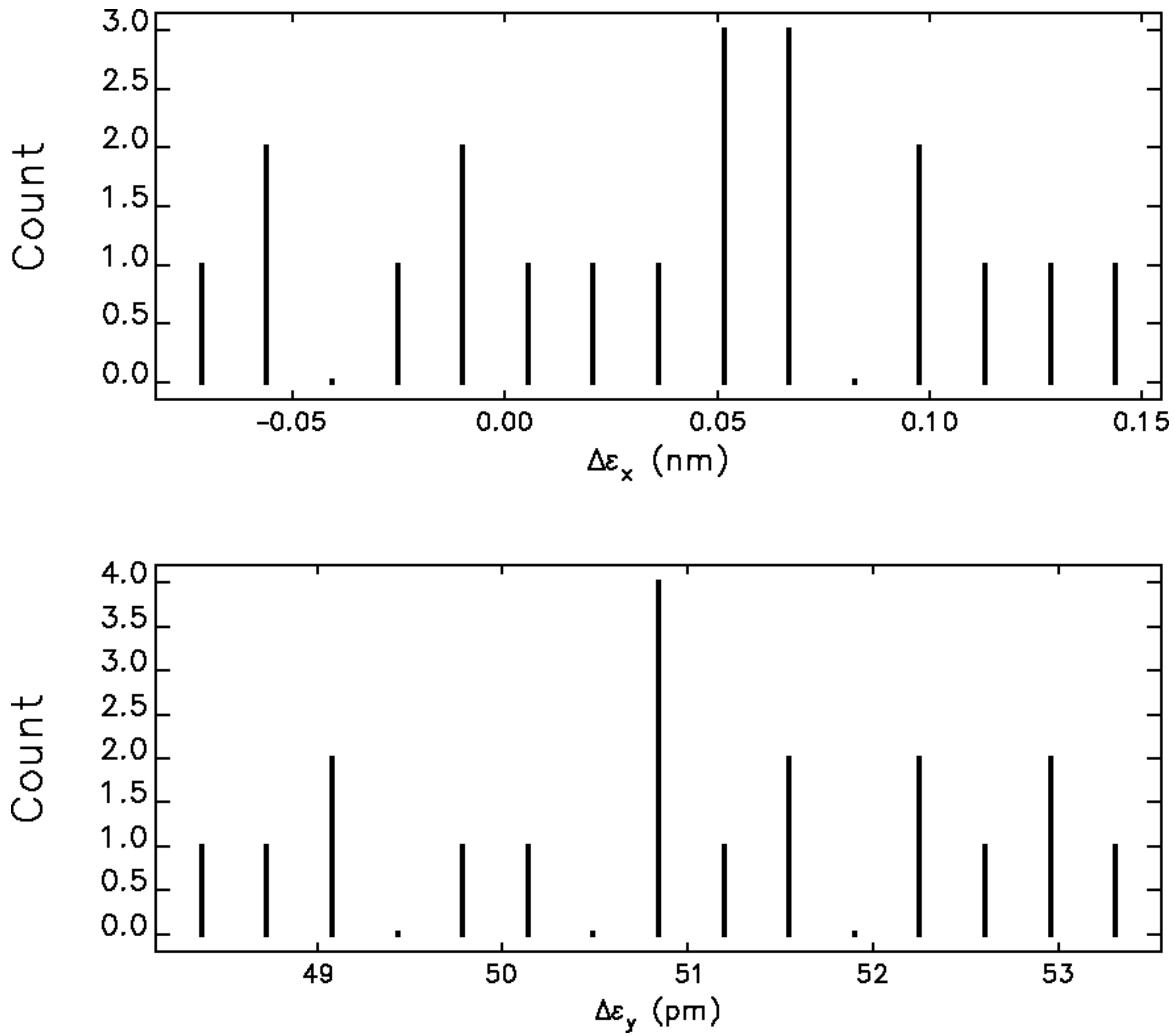




[1]V. Sajaev and L. Emery, EPAC 2002, p. 742
[2]L. Emery

Lattice Coupling Between Cavities

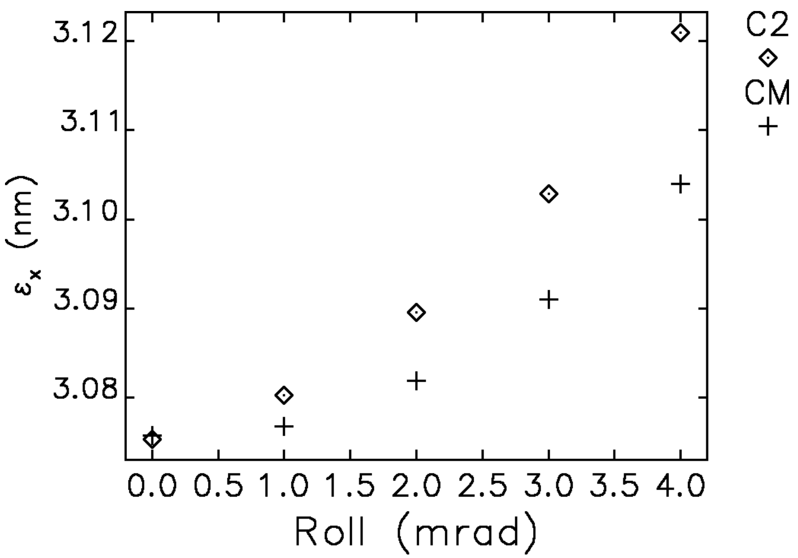
- May have quad and sextupole roll
- Roll is ~0.25 mrad rms[1]
- Performed random roll simulations with 20 seeds
- No coupling correction was employed

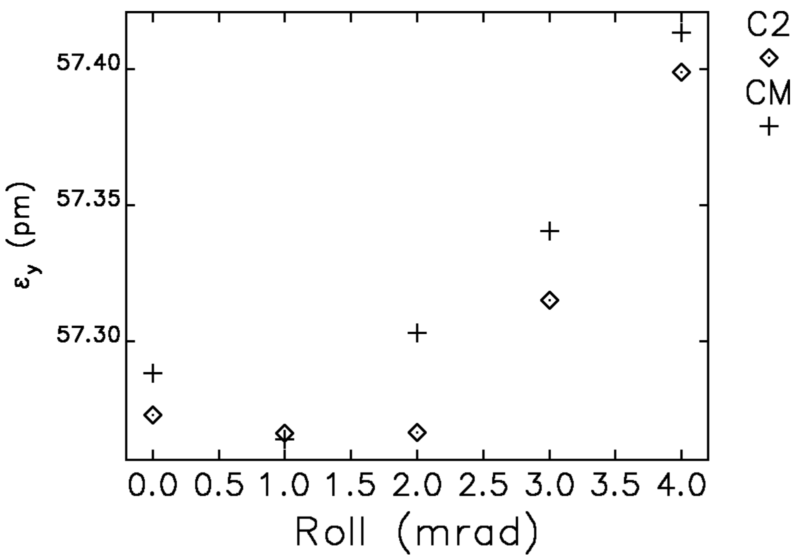


[1]H. Friedsam

Cavity Roll

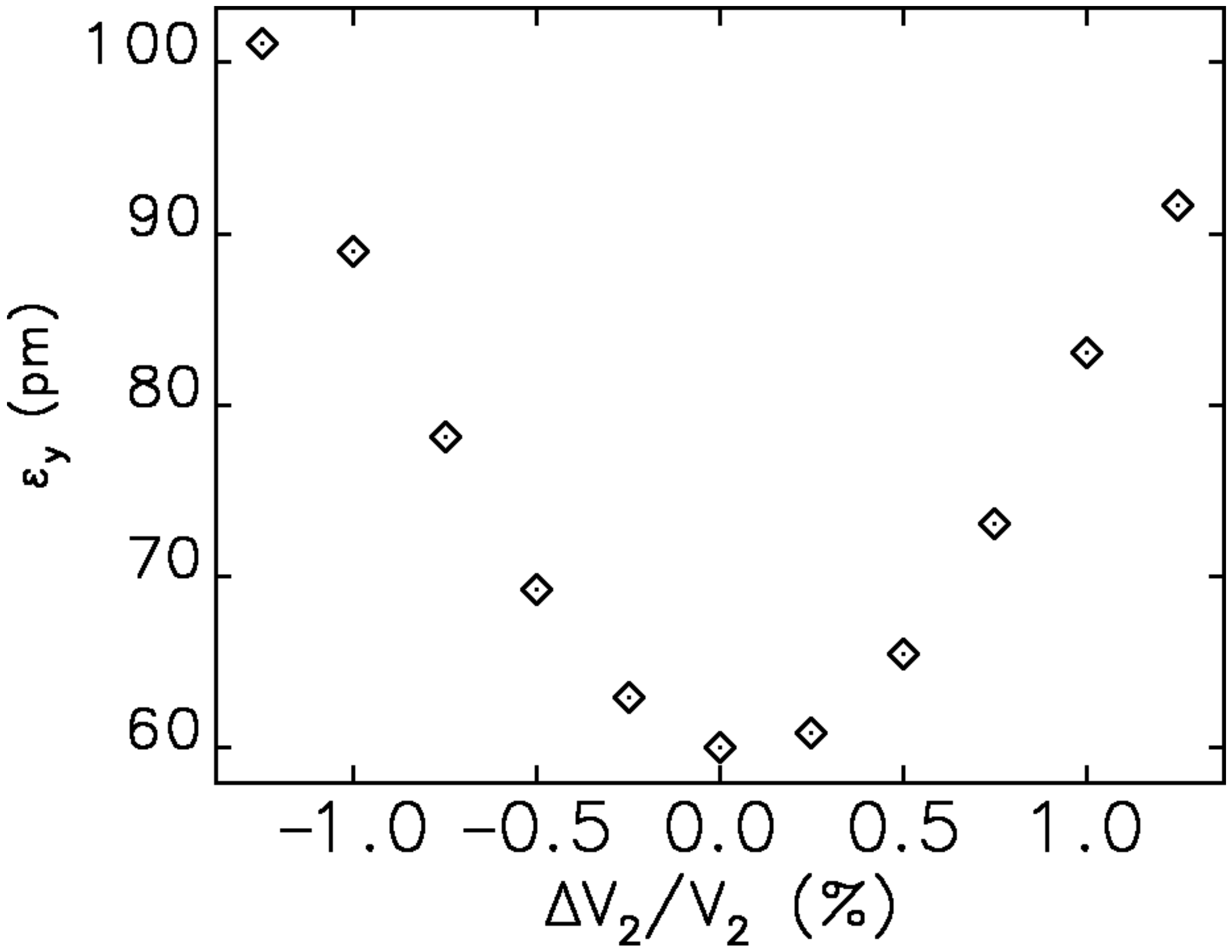
- Cavities may be rolled relative to machine vertical
- Simulated two cases
  - Cavities rolled the same amount (CM)
  - 2^{nd} cavity only rolled (C2)
- Neither is a problem at few mrad level



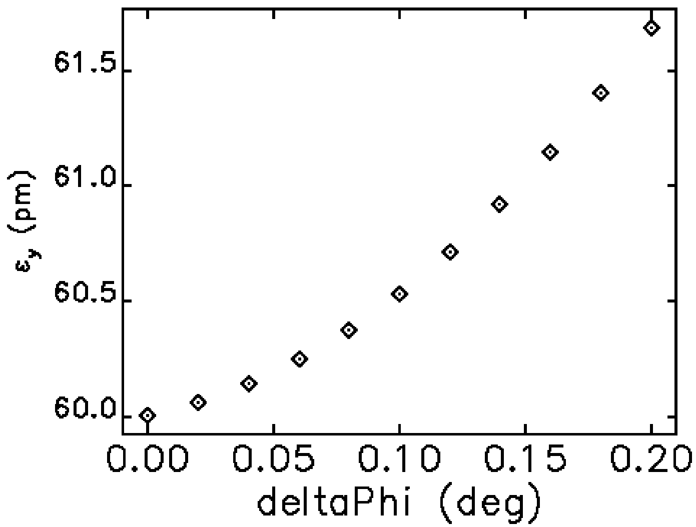


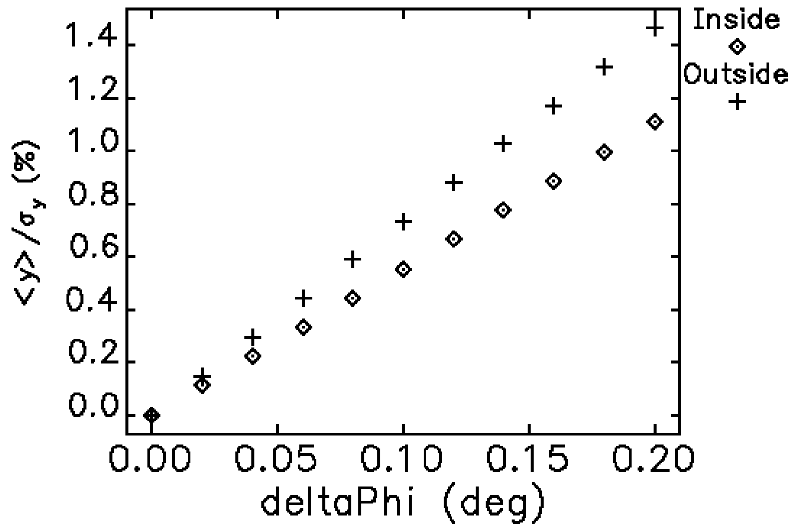
Intercavity Voltage Error

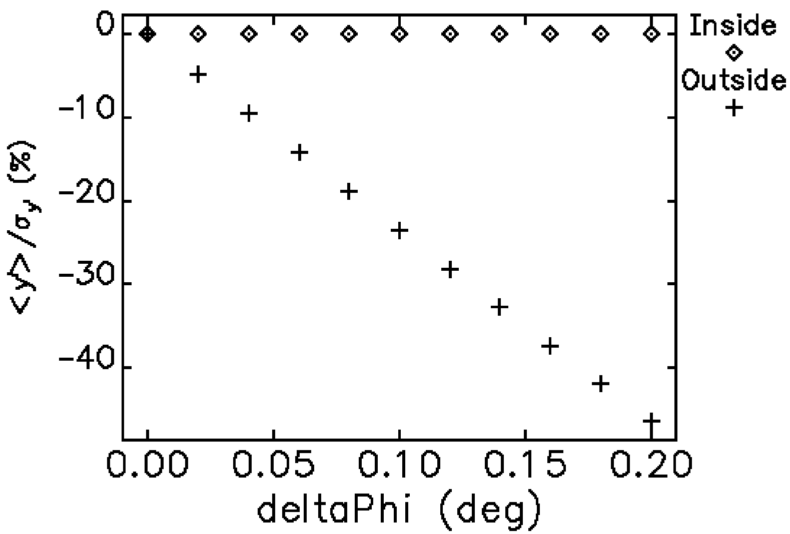
- Imparted errors to one of the cavities



Intercavity Phase Error







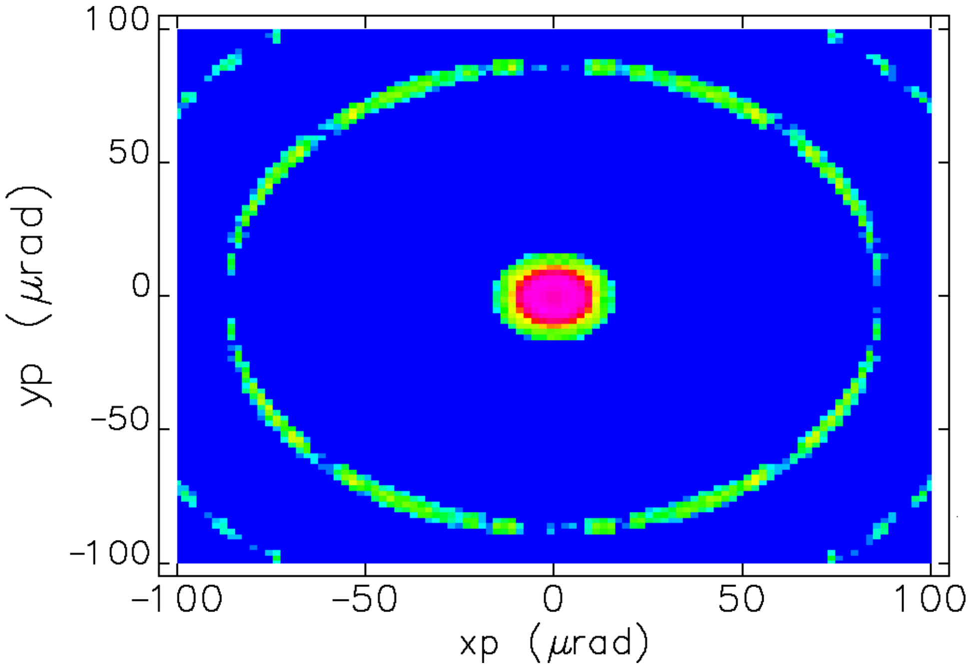
Most difficult issue is orbit disturbance outside the inter-cavity region.

X-ray Slicing Simulation

- X-ray pulse duration can be estimated assuming gaussian pulse shapes

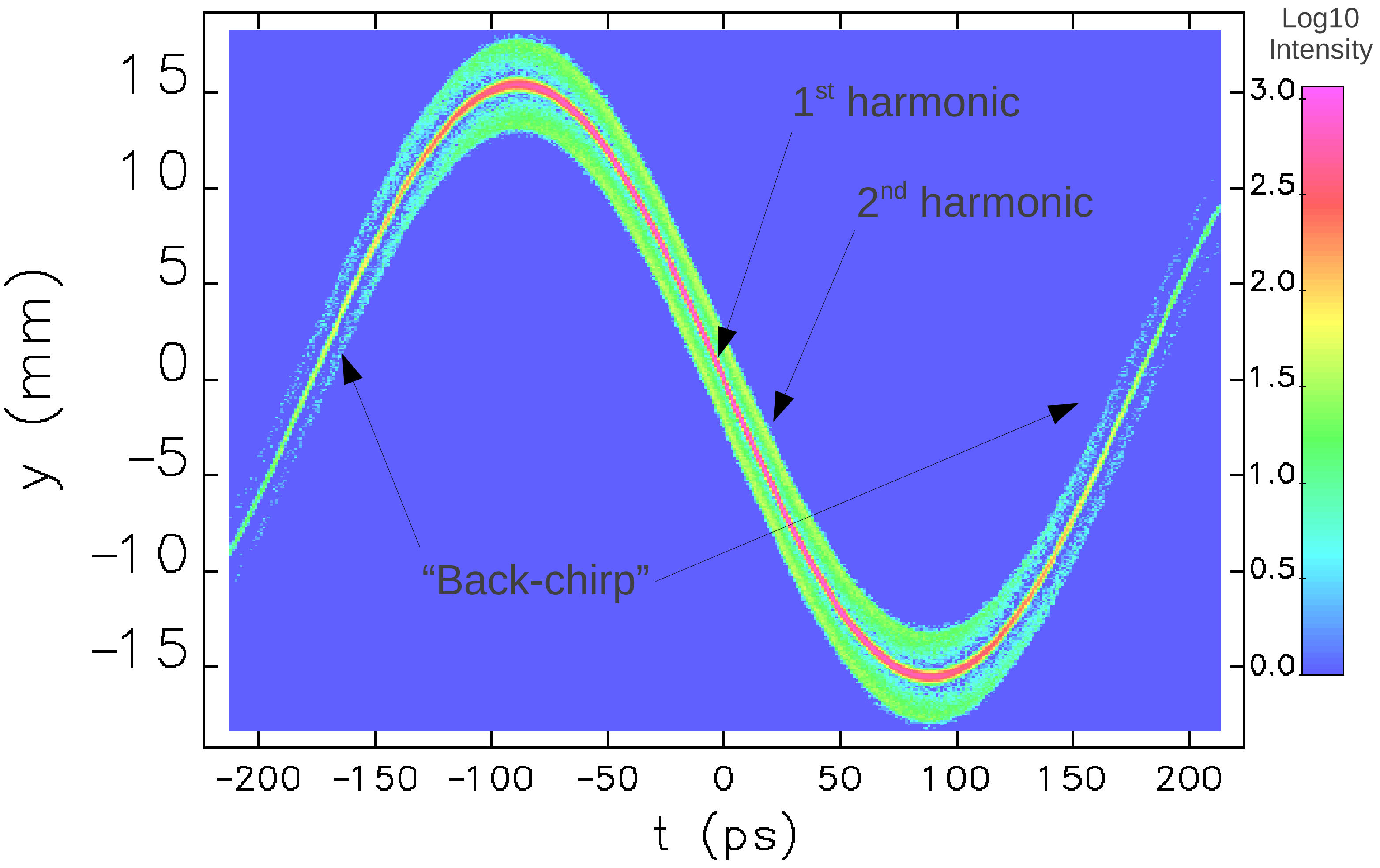
$$\sigma_{y',rad} \approx \sqrt{\frac{\lambda}{2L_u}}$$

- Program **sddsurgent**[1] computes the radiation pattern for given undulator parameters
- Includes detailed central cone distribution and off-axis higher-harmonics
- Convolve this with electron distribution from **elegant**
- Drift and slit simulation done with **elegant**



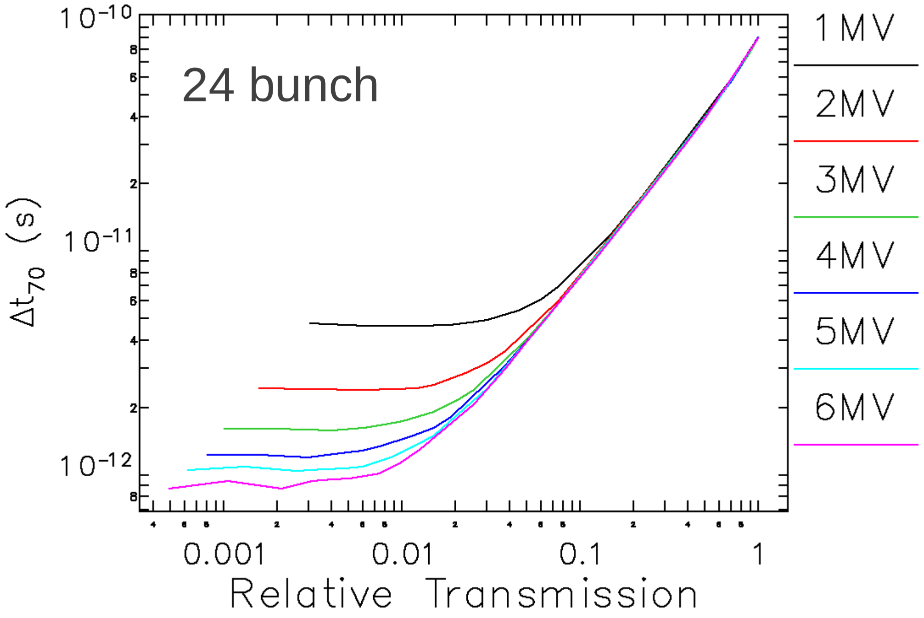
[1]H. Shang, R. Dejus, R. Walker, M. Borland.

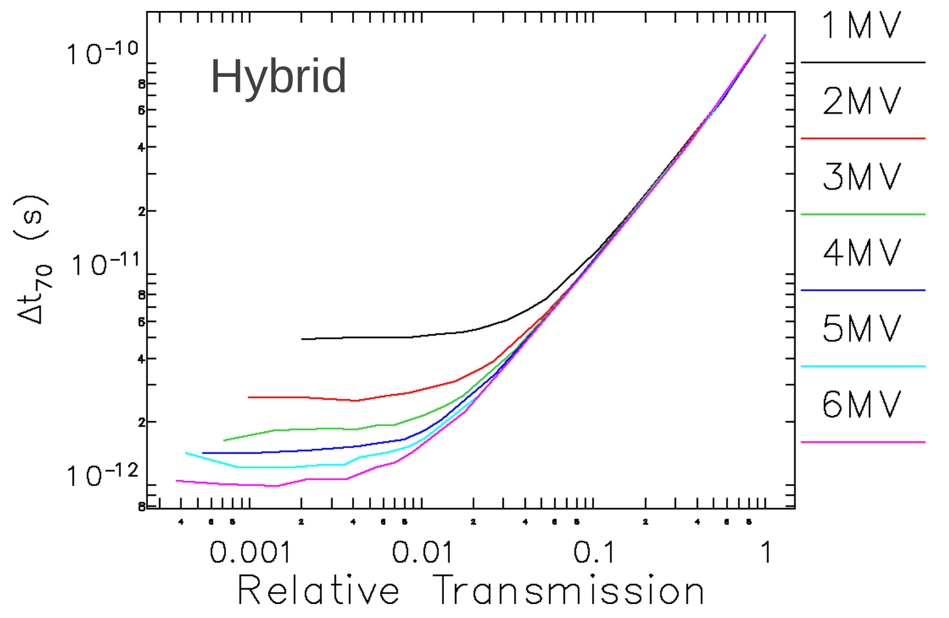
Radiation Distribution 26.5m from Source (Hybrid Mode)



26.5m is the distance to an aperture in the ID7 beamline. Aperture is typically set at 0.5 mm in both planes. (E. Dufrense.)

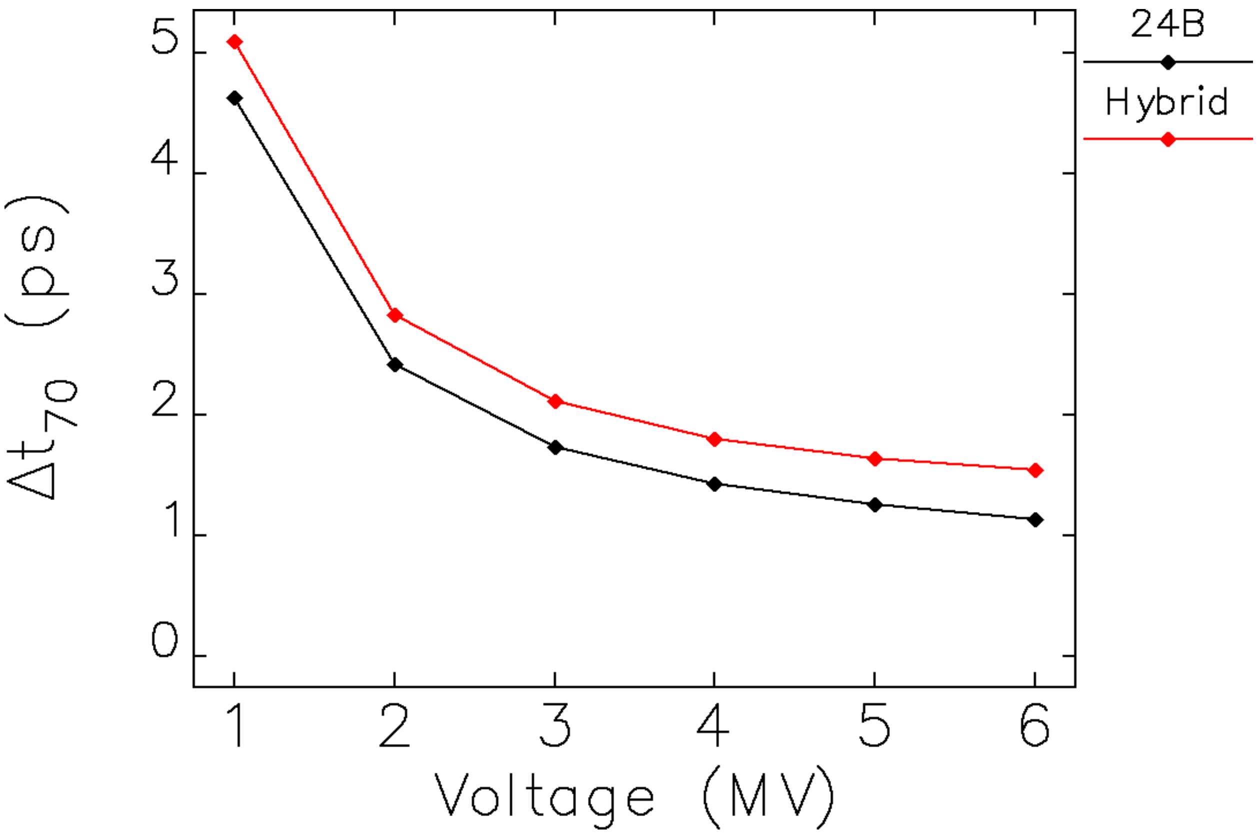
X-ray Slicing Results (2.4-m U33, 10keV)





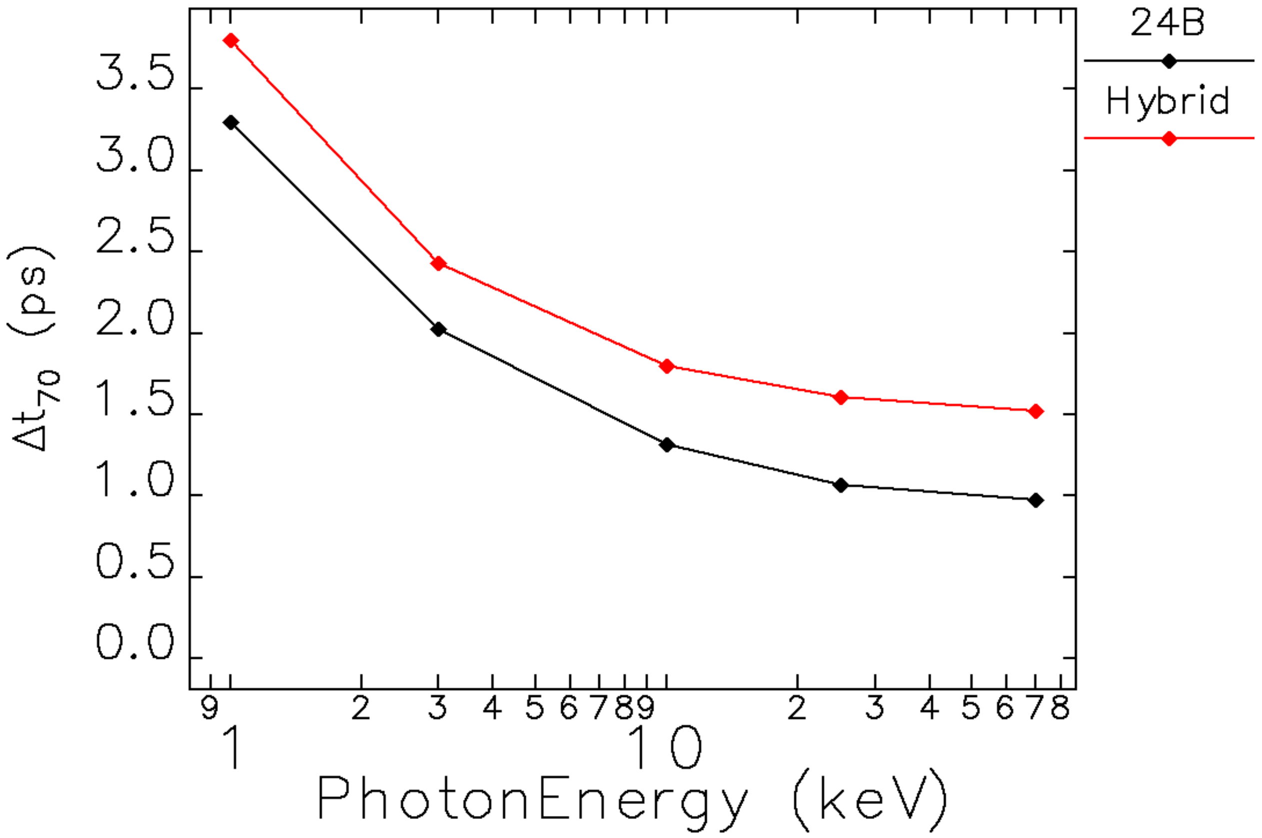
- Two slits at 26.5 m
  - Vertical slit is varied from ±100 mm to ±0.010 mm
  - Fixed horizontal slit of ±0.25 mm (E. Dufrense)
    - Helps to remove the 2nd-harmonic pollution

Results for Constant 1% Transmission



- 24-bunch mode better due to smaller emittance
- Diminished returns evident even at 4 MV
- No compelling reason to go above 4 MV
  - Even 2 MV might be acceptable...

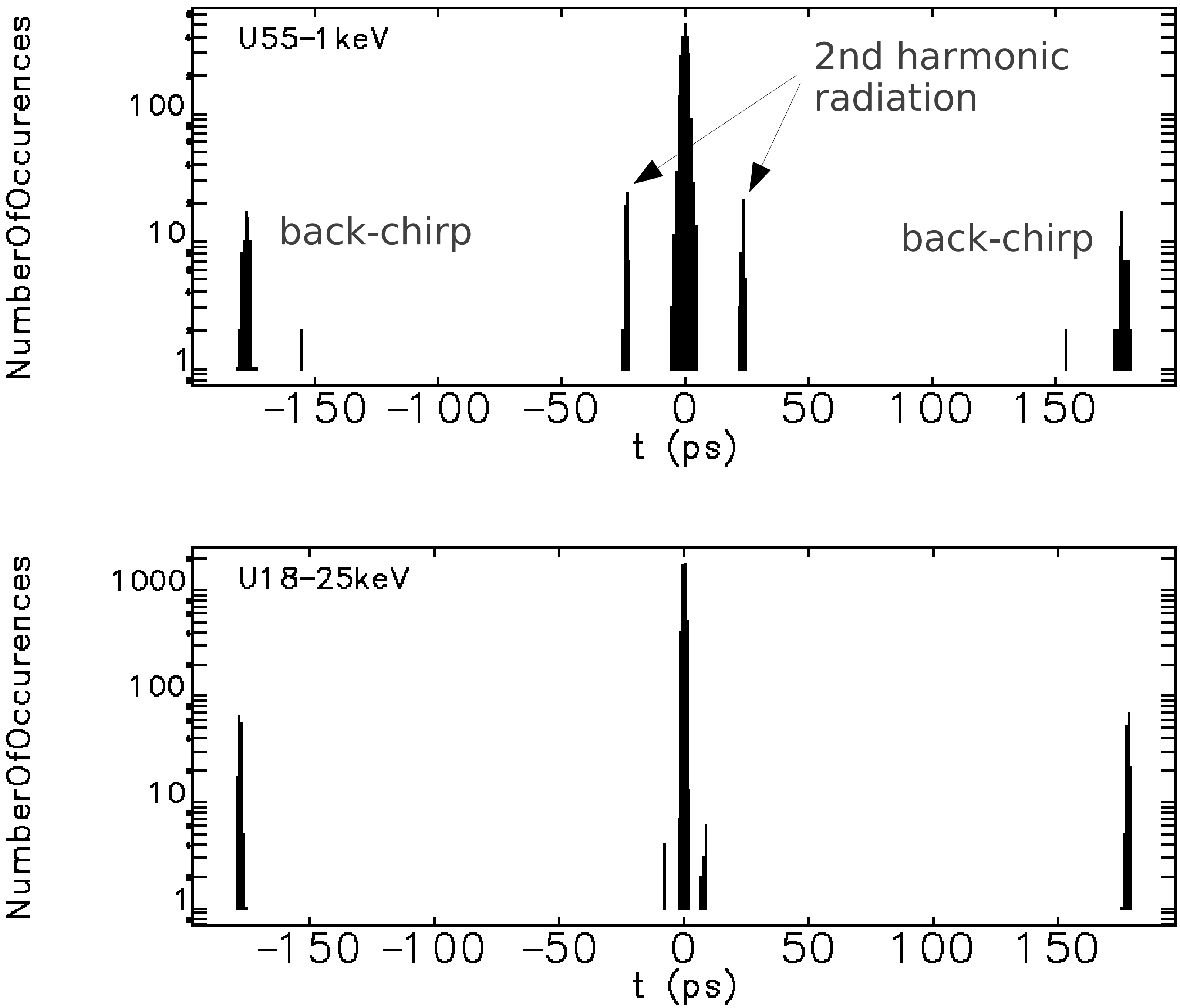
Effect of Photon Energy (4 MV, 1% Trans.)[1]



- Problem: intrinsic divergence of the photon beam increases as photon energy decreases
- Assumed 2.4-m ID: variously used U18, U33, and U55 devices

[1]M. Borland, OAG-TN-2008-016, April 16, 2008.

Details of X-ray Slicing for Hybrid Mode[1]



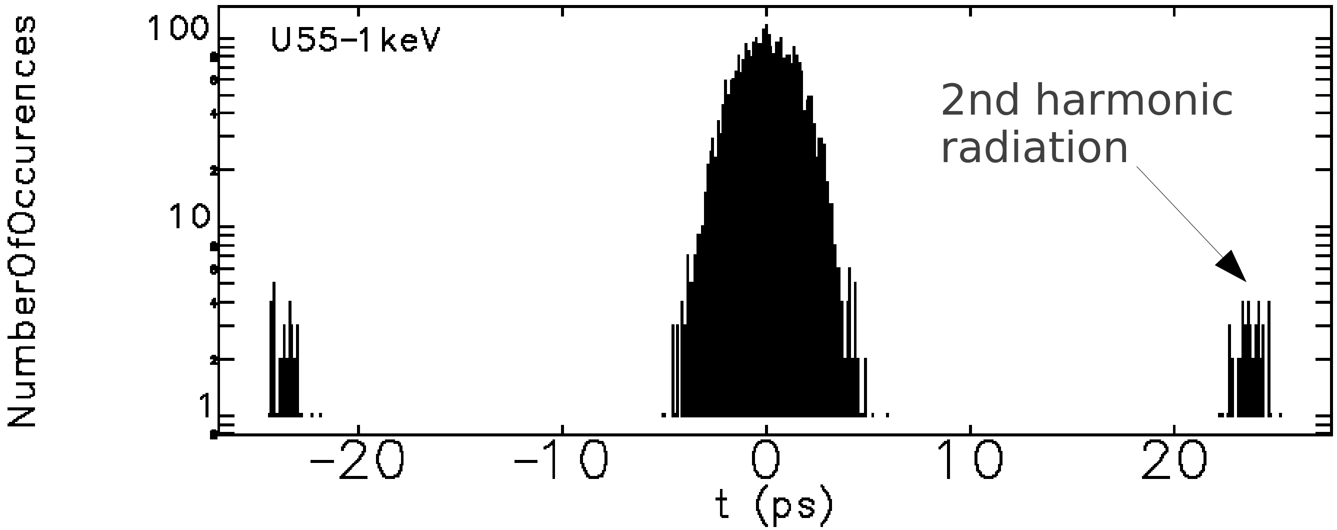
Back-chirp pulses have about 3% of the intensity of the central pulse.

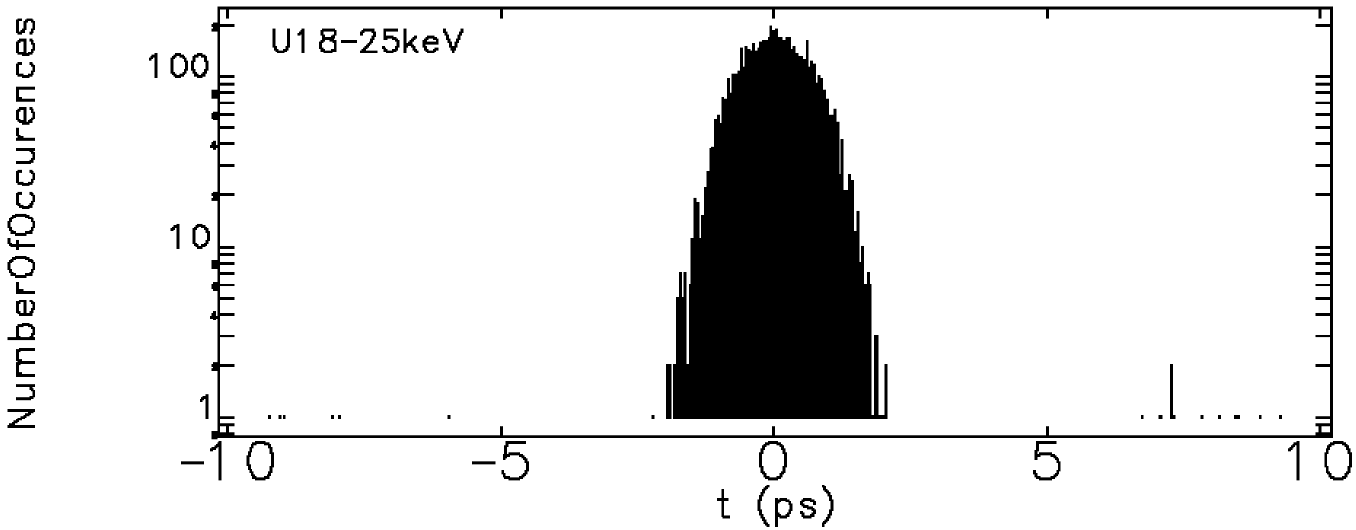
2nd harmonic pulses seen with up to ~2% of central intensity.

Slits: H=0.5 mm, V=0.2 mm

[1]M. Borland, OAG-TN-2007-016, 3/16/07.

Details of X-ray Slicing for 24 Bunch Mode





Back-chirp pulses have about 0.02% of the intensity of the central pulse and are not seen here.

2nd harmonic pulses seen with up to ~2% of central intensity.

Slits: H=0.5 mm, V=0.2 mm

Conclusion

- Zholents' scheme for making short x-ray pulses was simulated in detail
- Emittance growth is a primary concern
  - Sextupole optimization makes this manageable
  - Deflecting voltage is limited, however
- Predicted pulse durations approach 1ps FWHM for hard x-rays
- Pulse structure has complex features due to higher harmonics, long electron bunch
- Tolerances are tight but seem achievable
- APS is pursuing this as part of our upgrade